NASA TECHNICAL TRANSLATION NASA TT F-14,071

CESIUM VAPOR CONDENSATION FROM ARGON FLOWS

V. M. Borishanskiy, I. I. Palayev, K. M. Aref'yev,
N. I. Ivashchenko, T. V. Zablotskaya, B. M. Khomchenkov,
and N. M. Fishman

Translation of "Kondensatsnya Parov Tseziya Iz
Potoka Argona," Inzhenerno-Fizicheskiy Zhurnal,
Vol. 20, No. 4, April, 1971, pp 600-606.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 NOVEMBER 1971

CESIUM VAPOR CONDENSATION FROM ARGON FLOWS

V. M. Borishanskiy, I. I. Palayev, K. M. Aref'yev
N. I. Ivashchenko, T. V. Zablotskaya, B. M. Khomchenkov,
and N. M. Fishman[1]

ABSTRACT: The condensation of small cesium vapor admixtures from laminar argon flows in tubes and turbulent flow in banks of tubes was studied under conditions where mist formation was likely to occur. It is found that for turbulent flow, mist formation in the boundary layer has only a slight effect on the diffusion condensation process. Calculations without allowance for mist formation and deposition are shown to lead to satisfactory results.

INTRODUCTION

Cesium has been suggested for use as an ionizing additive in magnetohydrodynamic generators with a closed cycle, operating with inert gas. The cesium must be removed from the gas flow beyond the magnetohydrodynamic channel. Partial separation may be achieved by condensation of the cesium on the cooled surfaces of heat exchangers. /600*

The amounts of cesium added to the inert gases are small (less than 0.1% mole). The condensation of small amounts of additive is determined by diffusion of vapor through a gas boundary layer to the cooled surface [1]. It is possible to use in the calculations the analogy which exists between heat and mass exchange; the limitations to the analogy which are associated with the influence of the Stefan current, are insignificant at low cesium concentrations. However, fog formation [2] may have an effect. But when a gas is cooled, the vapors in the flow and in the boundary layer may become supersaturated due to the sharp drop in saturation pressure with decreasing temperature. Then homogeneous (volume) condensation — fog formation begins. With a normal concentration of foreign condensation centers in a gas (grains of dust, etc.) volume condensation begins at slight supersaturation $p/p_s = 1.02 - 1.12$ [2].

[1] Central Boiler-Turbine Institute Imeni. I. I. Polzunou, Leningrad.
* Numbers in the margin indicate foreign pagination.

The purpose of the present paper was to study the condensation of cesium from a flow of an inert gas (argon) under conditions when fog formation can occur. The first series of experiments in which the influence of fog formation was studied was conducted in stainless steel tubes with an internal diameter of 4.5 millimeters and 1 millimeter and a wall thickness of 0.2 millimeters. The length of the tubes was 300 millimeters. During the experiment, argon containing cesium in amounts from 1.1×10^{-4} kilograms per kilogram to 10×10^{-4} kilograms per kilogram was fed into the tube (the cesium was evaporated beforehand from a special vessel). The argon temperature at the tube inlet was 723°K, while at the tube outlet it was practically the same as the tube wall temperature. The tube was placed in a glycerine bath whose temperature (and therefore the temperature of the tube walls) varied between 285 and 433°K. The flow rate in the tube (on the basis of the average gas temperature) varied from 1.5 to 65 meters per second and the Reynolds member varied from 160 to 1550 (the flow was either laminar or transitional). At the tube outlet, the argon entered absorption vessels where it was bubbled through a solution of nitric acid. Binding of the cesium took place. The final concentration of cesium in the argon was determined on the basis of a chemical analysis of /601
the solution with a known consumption of argon. The cesium that condensed on the walls of the tube was washed off with water after the experiment. A chemical analysis of the solution gave the amount of cesium which had condensed. On the basis of the loss of weight of the evaporating vessel, it was also possible to determine the amount of cesium that was admitted to the flow of argon as it entered. The cesium balance was determined with an accuracy of 0.5%.

Figure 1 shows the results of several experiments, in the form of the dependence of the relative sedimentation of cesium Z on the inlet cesium concentration C_0 and the wall temperature T_{wall}. It is obvious that the relative sedimentation decreases as the cesium concentration C_0 increases. At low wall temperatures (285°K, 373°K), the sedimentation is less than at higher temperature (403°K, 433°K). Sedimentation again decreases at a wall temperature of 473°K.

The relationship of the relative cesium sedimentation to the inlet concentration and the wall temperature may be explained by the influence of fog

formation. When the inlet concentration increases (partial pressure of cesium), fog formation begins close to the tube inlet (Figure 2,a). This means that there is a decrease in the relative sedimentation ahead of the fog-formation zone:

$$Z = \frac{p_0 - p^*}{p_0} . \qquad (1)$$

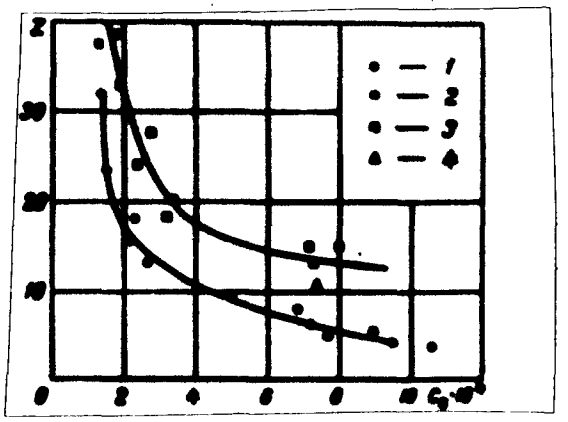

Figure 1. Relative Sedimentation of Cesium Z (%) in Tube Depending on Inlet Cesium Concentration C_0 (kg/kg). Argon flow rate $2.1 \cdot 10^{-5}$ lg/sec; velocity ~ 1.5 m/sec. Averaging lines corresponding to wall temperatures 403 to 433°K (upper line) and 373°K (lower line).

Where p* is the partial pressure corresponding to the point of intersection of curves p and p_s. The droplets of fog themselves are carried away by the flow and there is practically no sedimentation on the walls under the conditions that prevailed in the experiments we performed. A control experiment was performed with a cube 2 meters long, twisted into a coil. The considerable increase in the length of the tube did not lead to an increase in sedimentation.

The fog develops not only at the center of the flow but even more in the boundary layer next to the walls. In Figure 2,b, we have plotted the boundaries of the zone of saturation of cesium vapor (obtained from calculations) at the walls of a tube for one of the regimes (with 2 inlet concentrations of cesium). As we can see, the area within which fog formation is possible begins close to the inlet cross section. Initially the thickness of this region

is slight and sedimentation on the walls is possible; then the thickness of this area increases and in the final analysis the zone of fog formation covers the entire flow cross section. With a high cesium concentration, the fog-formation zone is thicker and covered the flow cross section sooner. When the wall temperature decreases, the thickness of the fog — formation zone also increases and the cesium sedimentation decreases. On the other hand, when the wall temperature increases the zone of fog formation becomes thinner and fog appears later at the center of the flow. This promotes an increase in sedimentation. However, as the wall temperature increases the drop in the partial pressure of cesium decreases in the flow and at the wall (at the surface of the film of condensate). The partial pressure of the cesium at the wall is equal to the saturation pressure at the wall temperature; this pressure increases with increasing wall temperature. In the final analysis, cesium sedimentation begins to decrease at elevated temperatures. There is an optimun wall temperature. For the conditions of the experiment we performed, this temperature lies between 400 and 430°K. Theoretical calculations lead to the same result. /602

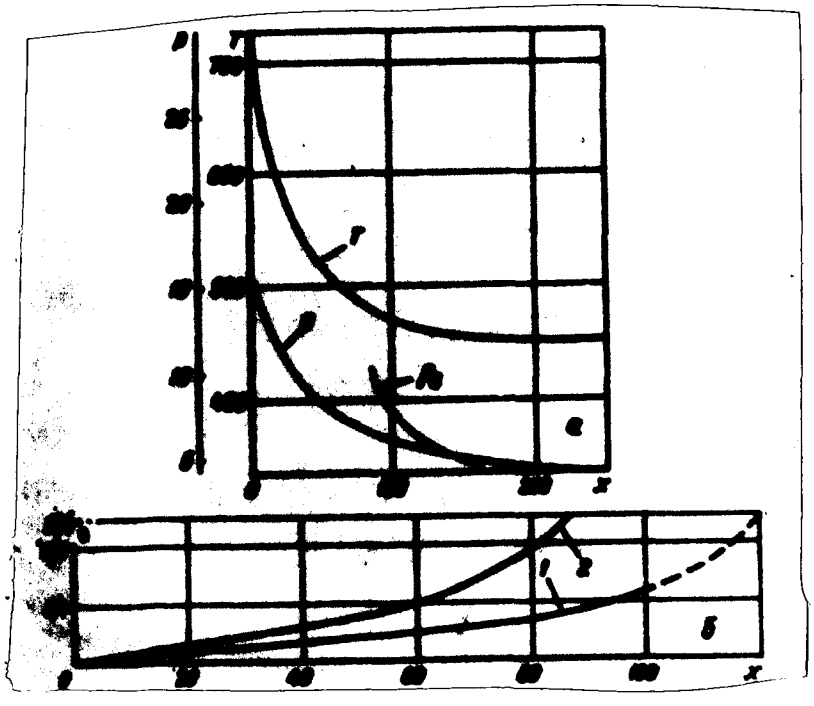

Figure 2. Distribution of Gas Temperature T (°K), Partial Pressure of Cesium p (N/m^2) and Pressure of Cesium Saturation p_s (N/m^2) Along Tube Length x (mm) (a) and Boundary of Region of Fog Formation Near Tube Walls (6). Argon Flow Rate 2.1 · 10^{-5} kg/sec Velocity ~ 1.5 m/sec.

Cesium sedimentation decreases significantly due to fog formation at the walls. Calculations of cesium condensation using analogy and solutions of problems on heat exchange in laminar flow in tubes give overly high results if we take into account only the fog formation in the flow itself and fail to consider the influence of fog formation at the walls. As the Reynolds number increases, especially with a transition to a turbulent flow regime, the negative effect of fog formation at the walls will decrease due to the decrease in thickness in the boundary layer. This is supported by the results of [3] involving condensation of potassium and cesium additives from an argon flow in a tube (Reynolds numbers up to 11500).

The second basic series of experiments was performed with a transversely streamlined tube bundle. A diagram of the system is shown in Figure 3. The argon was pumped through a closed circuit made of stainless steel by a centrifugal gas blower./ Ahead of the gas blower, the argon was heated by electric heaters to 543 — 623°K. The gas blower itself was also heated. After passing /603 through the gas blower, the argon was mixed with cesium, the latter being evaporated from a special vessel. / The working section was the transversely streamlined bundle with a checkerboard arrangement of tubes measuring 12 millimeters in diameter. The relative spacing across the front was equal 2 (the number of tubes per row was 5, the height of the tubes was 40 millimeters), while along the depth of the bundle it was 1.5. The bundle consisted of two individual parts, connected in series. The first part of the bundle through which the argon traveled consisted of 8 rows of tubes while the second consisted of 24 rows (with subdivision into 3 sections of 8 rows of tubes each). The total working length of the bundle was 60 millimeters.

The tube bundle was cooled from inside by air. The air, applied by a special gas blower, passed in succession through the three sections of the second part of the bundle (from the argon outlet end) and then into the first part of the bundle. The argon flow through the bundle varied from 0.028 to 0.067 kilograms per second, the velocity in the narrow cross section was 3 to 8 meters per second, the Reynolds number varied with a diameter of the tube from 1200 to 3000. The argon temperature at the bundle inlet varied from 543 to 623°K and the temperature at the bundle outlet was 353 to 403°K.

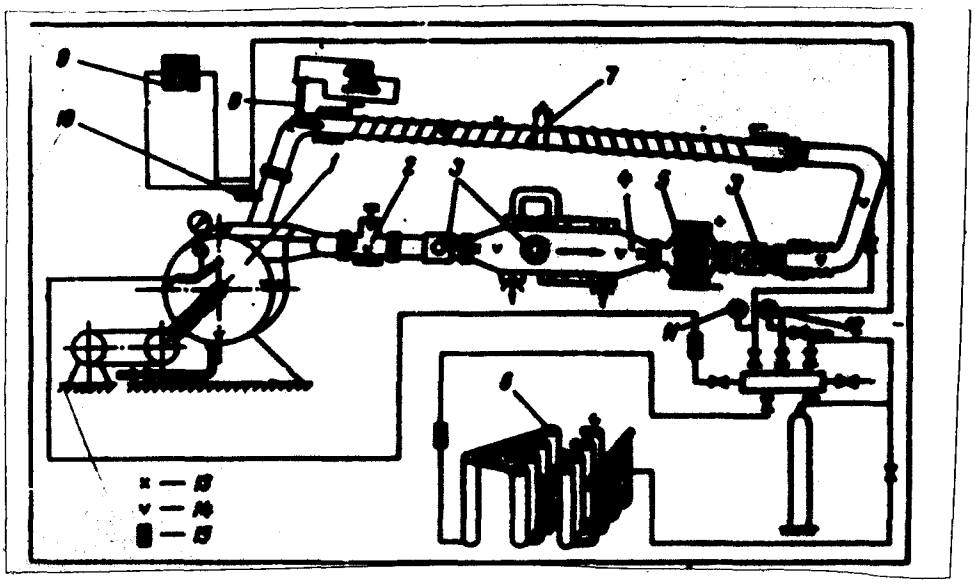

Figure 3. Scheme of Experimental Installation for Studying Cesium Condensation in Tube Bundle; 1, Gas blower; 2, Evaporator; 3, Plug for openings; 4, Working section; 5, Heater; 6, Gas cleaner, 7; Heater; 8, High-speed tube; 9, Zero-instrument; 10, Pressure gage; 11, Manovacuometer; 12, Sample manometer; 13, Main thermocouples; 14, Control thermocouples; 15, Rotameter.

The cesium concentration in the argon ahead of the bundle and downstream from it was determined by a chemical analysis of gas samples. The sampled gas was bubbled through a solution of nitric (or sulphuric) acid and the gas consumption was measured. The cesium concentration at the bundle inlet varied from $2 \cdot 10^{-4}$ kilograms per kilogram to $11 \cdot 10^{-4}$ kilograms per kilogram. In most of the experiments of the first series, the relative sedimentation of cesium Z in the bundle was 35 to 45% of the added amount of cesium, while in the second series (with parallel flow of cooling air over all the tubes in the bundle) it was 50 to 65%. Sedimentation reached 15% in only one experiment when the fog formation began close to the inlets.

Experimental data on cesium sedimentation were compared with calculated values. The variation in temperature and partial pressure of cesium along the length of the bundle were determined from relationships following from equations /604 of heat and mass exchange:

$$T = T_{wall} + (T_0 - T_{wall}) \exp(-kx), \quad (2)$$

$$p = p_{wall} + (p_0 - p_{wall}) \exp(-nx), \quad (3)$$

where

$$k = \frac{Nu}{Pe} \cdot \frac{F_{vapor}}{F_{live\ section}} \cdot \frac{1}{L}, \quad (4)$$

$$n = \frac{Nu_D}{Pe_D} \cdot \frac{F_{vapor}}{F_{live\ section}} \cdot \frac{1}{L}. \quad (5)$$

In the calculation, the bundle was divided into several zones. Within the limits of a zone, the temperature of the wall determined with consideration of heat exchange with the air inside the tubes was considered to be constant. The physical values were related to the average gas temperature in the zone. The values of the numbers Nu and Nu_D were determined as functions of the numbers Pr and Pr_D (for Nu_D), and also from the design characteristics of the bundle using a formula from [4]. The diffusion coefficient D_a of the cesium vapor in the argon was based on data from [5].

On the basis of the calculations, we plotted the curve showing the change in temperature, partial vapor pressure of cesium and pressure of saturated cesium vapor along the length of the bundle. The intersection of the latter two curves determines the beginning of the zone of fog formation in the flow (Figure 4). It was assumed that the sedimentation of cesium in the zone of fog formation may be disregarded. The relative sedimentation prior to the zone of fog formation was determined by relationship (1). The ratio of the experimental and calculated values of Z is shown in Figure 5. The value of this relationship was close for unity for most of the experiments.

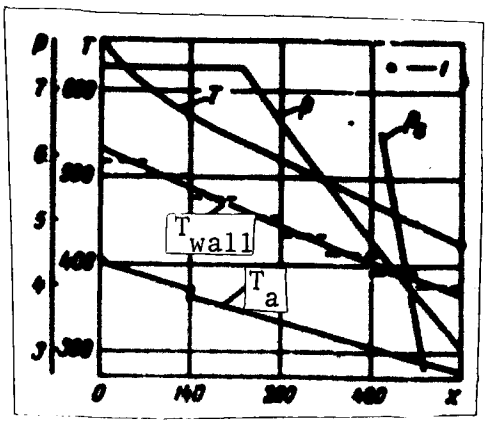

Figure 4. Calculation Curves of Argon T, Air T_a and Walls T_{wall} of Change in Pressure (N/m^2) and Saturation Pressure p_s (N/m^2) of Cesium Along Length of the Bundle for One of the Experiments (1, Experimental Points). Argon Flow Rate 0.045 kg/sec; Inlet Concentration of Cesium $C_0 = 2.3 \cdot 10^{-4}$ kg/kg.

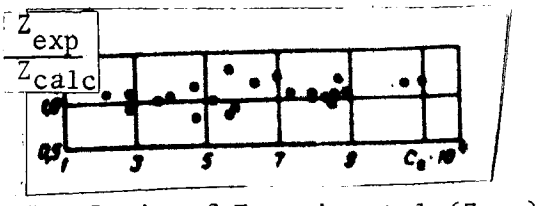

Figure 5. Ratio of Experimental (Z_{exp}) to Calculated (Z_{calc}) Cesium Sedimentation at Various C_0 (kg/kg).

Fog formation in the boundary layer at the surface of the tubes may begin somewhat earlier than in the middle of the flow. However, with turbulent flow the influence of fog formation near the wall on the process of diffusion condensation is very slight and is within the limits of accuracy of the experiments. As far as fog formation in the volume is concerned, the droplets of fog may be /605 partly deposited on the tubes as they are carried there by the flow. The sedimentation of droplets of fog or the aggregates of molecules which precede them has been observed in [6], in which the condensation of mercury vapor from an air flow was studied with transverse streamlining of tube bundle.

An analysis [5] shows that for the conditions of the experiments which were performed the calculation using the suggested method (without consideration of fog formation in the boundary layer and sedimentation of fog during flow around the bundle) will provide results that are correct on the average.

Nonemclature

p, partial pressure of cesium vapor; p_s, pressure of saturated cesium vapor; Z, relative sedimentation of cesium; T, flow temperature; T_0, inlet flow temperature; T_{wall}, wall temperature; x, coordinate along bundle length; p_0, partial pressure of cesium vapor at inlet; p_{wall}, partial pressure of cesium vapor near wall surface equal to the pressure of saturates vapors at wall temperature; Nu, thermal Nusselt number; a, heat transfer coefficient; d, diameter of tube; λ,

gas thermal conductivity; Pe, thermal Peclet number; w, flow velocity; a, gas thermal diffusivity; F_{vapor}, external surface of tube bundle; $F_{live\text{-}section}$, live-section area of bundle; L, total length of bundle along gas flow; Nu_D, diffusional Nusselt number; a_D, diffusional transfer coefficient; D_{12}, diffusivity; Pe_D, diffusional Peclet number; Re, Reynolds number; ν, kinematic viscosity of gas; Pr, thermal Prandti number; Pr_D, diffusional Prandti number (Schmidt number).

REFERENCES

1. Frank-Kamenetskiy, D. A., *Diffuziya I Teploperadacha V Khimicheskoy Kinetike* [Diffusion and Heat Transfer in Chemical Kinetics], Moscow, "Nauka" Press, 1967.
2. Amelin, A. G., *Teoreticheskiya Osnovy Obrazovaniya Tumana Pri Kondensatsii Para* [Theoretical Bases of the Formation of Fog in the Condensation of the Vapor], Moscow, "Khimiya" Press, 1966.
3. Styrikovich, M. A., I. L. Mostinskiy and Ya. N. Vizel', *Teplofizika Vysokikh Temperatur*, Vol. 6, No. 4, 1968; Vol. 7, No. 2, 1969.
4. Mochan, S. I., O. G. Revzina, V. A. Lokshin and A. Ya. Antonov, *Trudy TsKTI*, No. 82, Leningrad, 1968.
5. Khomchenkov, B. M., K. M. Aref'yev, V. M. Bortsshanskiy, I. I. Paleyev, N. I. Ivashchenko, I. G. Kholishey, R. I. Ulitiskiy and L. A. Suslova, *Teplofizika Vysokikh Temperatur*, Vol. 6, No. 6, 1968.
6. Styrikovich, M. A. and I. V. Godik, Izvestiya, AN SSSR, *Energetika i Transport*, No. 5 and 6, 1966.

Translated for the National Aeronautics and Space Administration under contract No. NASw-2037 by Techtran Corporation, P.O. Box 729, Glen Burnie, Maryland, 21061.